

Modified Gravity from a Geometric Perspective

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IBS: Introduction to IBS CTPU-CGA



IBS-CTPU-CGA spotlight



Institute for
Basic Science

Zi-Yu Tang

Gravitation, black-hole physics

Shadows, scalarization, and axion clouds.

black-hole shadows

scalarization

axion clouds



tangziyu@ibs.re.kr · Joined Aug. 2023

- Photon regions, black-hole shadows, and lensing as optical probes of strong gravity.
- Scalarization and critical behaviour in modified-gravity black holes.
- Axion-induced photon clouds around Kerr black holes.



IBS-CTPU-CGA spotlight



Institute for
Basic Science



Hui-Yu Zhu

General Relativity, black holes,
gravitational waves, cosmology

Black holes, gravitational waves, cosmology, and superradiance.

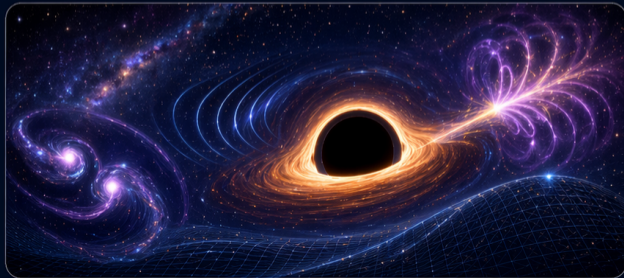
black holes

gravitational waves

superradiance

hzhuv@ibs.re.kr • Joined Nov. 2024

- General Relativity, black-hole physics, and gravitational-wave phenomena.
- Superradiance, black-hole perturbations, and strong-gravity signatures.
- Cosmological implications of gravity and compact objects.



IBS-CTPU-CGA spotlight



Institute for
Basic Science

Theodoros Nakas

Modified gravity, braneworld models, compact objects

Modified gravity, black-hole solutions, braneworlds, and compact objects.

modified gravity

black holes

braneworlds

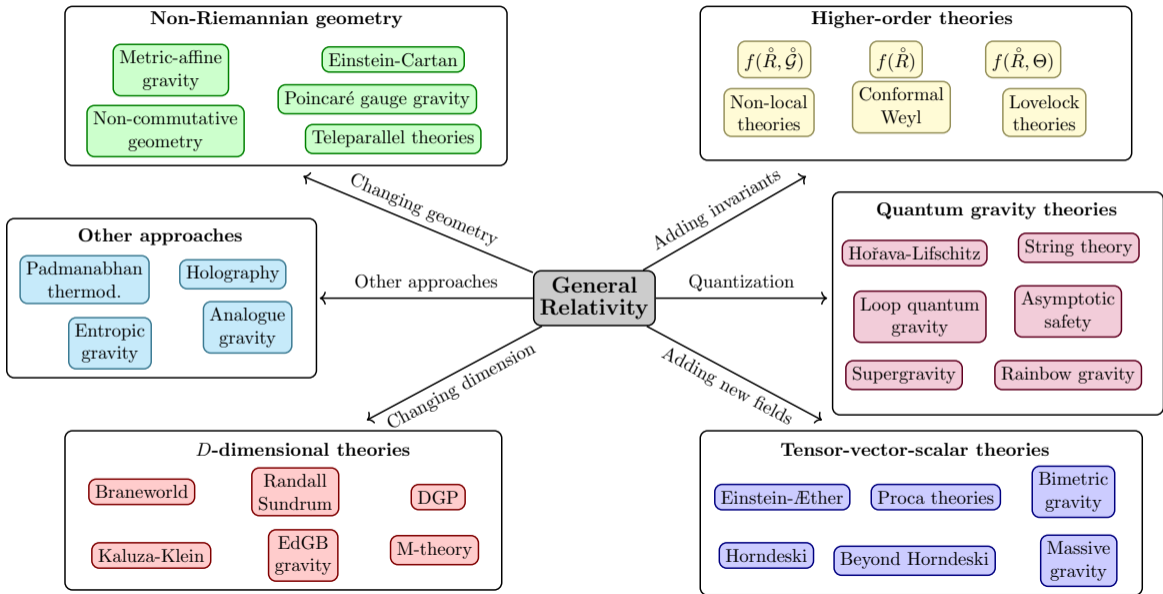


thnakas@ibs.re.kr • Joined Oct. 2024

- Modified gravitational theories and their phenomenology.
- Braneworld models, compact objects, and strong-gravity structure.
- Black-hole solutions and related properties in extended gravity.



How to modify gravity?



The usual assumptions

The gravitational field is described by a metric $g_{\mu\nu}$ and the connection is fixed to be the Levi-Civita connection $\Gamma^{\rho}_{\mu\nu}$.

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What do $g_{\mu\nu}$ and $\Gamma^{\rho}{}_{\mu\nu}$ do?

The metric $g_{\mu\nu}$ measures distances, time intervals, and angles. The connection $\Gamma^{\rho}{}_{\mu\nu}$ defines covariant derivatives and parallel transport, telling us how tensors are compared from point to point.

Consequence

$$T^{\rho}{}_{\mu\nu} = 0, \quad Q_{\rho\mu\nu} = \nabla_{\rho}g_{\mu\nu} = 0.$$

Only curvature remains as the carrier of gravity.

General Relativity as a geometric choice

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Why this is restrictive

The metric-affine viewpoint treats $g_{\mu\nu}$ and $\tilde{\Gamma}^{\rho}{}_{\mu\nu}$ as independent before imposing any constraints. GR is one corner of this larger space.

Why modify gravity?

Conceptual motivations

- quantum gravity is not understood;
- singularities indicate limits of the classical description;
- changing GR is one of the sharpest ways to understand why GR works.

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- dark energy and the cosmological constant problem;
- early-universe inflation and late-time acceleration;
- black holes and gravitational waves test the strong-field regime.

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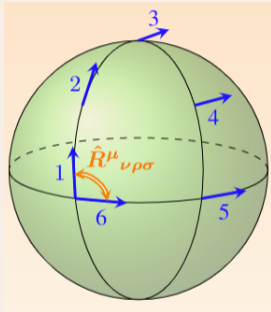
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Why is geometry a well-motivated route?

General Relativity ties gravity to spacetime geometry, so changing the geometric structure is a direct way to explore new gravitational theories.

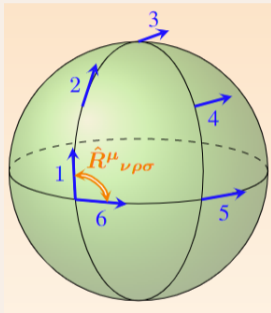
Curvature R



Directions change after transport
around a loop.

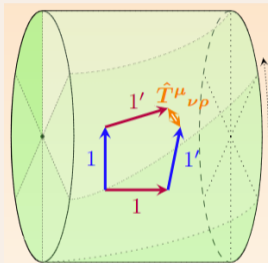
Curvature, torsion and nonmetricity

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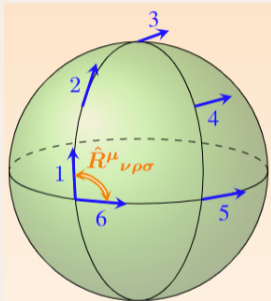
Torsion T



Infinitesimal parallelograms fail to close.

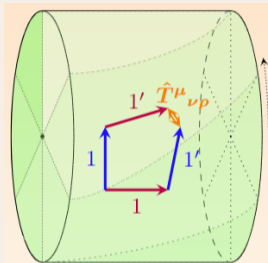
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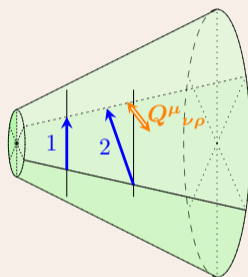
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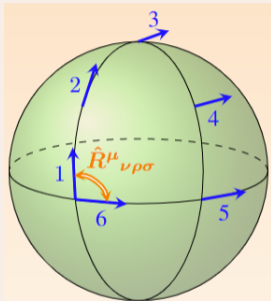
Nonmetricity Q



Lengths and angles change under transport.

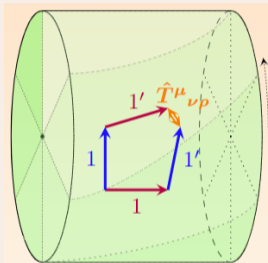
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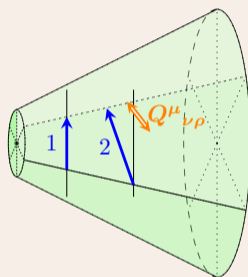
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Lengths and angles change under transport.

The entire talk is organized by deciding which of R, T, Q is allowed to be dynamical.

Independent variables

metric $g_{\mu\nu}$ + connection $\tilde{\Gamma}^{\rho}_{\mu\nu}$.

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Curvature, torsion and nonmetricity

$$\begin{aligned}\tilde{R}^{\mu}_{\nu\rho\sigma} &= \partial_{\rho}\tilde{\Gamma}^{\mu}_{\nu\sigma} - \partial_{\sigma}\tilde{\Gamma}^{\mu}_{\nu\rho} + \tilde{\Gamma}^{\mu}_{\lambda\rho}\tilde{\Gamma}^{\lambda}_{\nu\sigma} - \tilde{\Gamma}^{\mu}_{\lambda\sigma}\tilde{\Gamma}^{\lambda}_{\nu\rho}, \\ \tilde{T}^{\rho}_{\mu\nu} &= 2\tilde{\Gamma}^{\rho}_{[\nu\mu]}, \quad \tilde{Q}_{\rho\mu\nu} = \tilde{\nabla}_{\rho}g_{\mu\nu}.\end{aligned}$$

Metric-affine starting point

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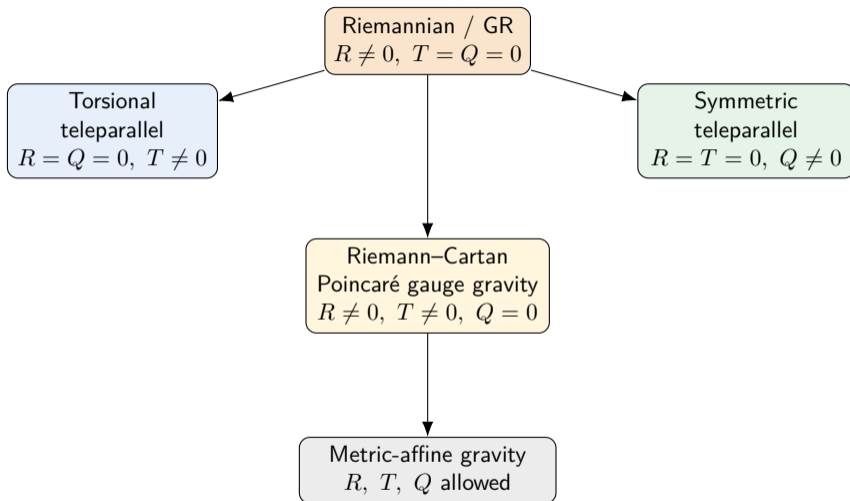
$$\tilde{T}^\rho{}_{\mu\nu} = 2\tilde{\Gamma}^\rho{}_{[\nu\mu]}, \quad \tilde{Q}_{\rho\mu\nu} = \tilde{\nabla}_\rho g_{\mu\nu}.$$

Decomposition

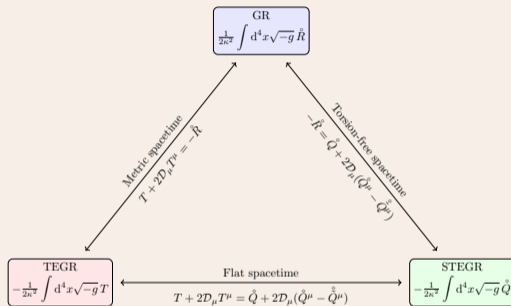
$$\tilde{\Gamma}^\rho{}_{\mu\nu} = \Gamma^\rho{}_{\mu\nu} + K^\rho{}_{\mu\nu} + L^\rho{}_{\mu\nu},$$

where K is a linear combination of torsion and L a linear combination of nonmetricity.

Different extended geometries give different types of gravitational theories



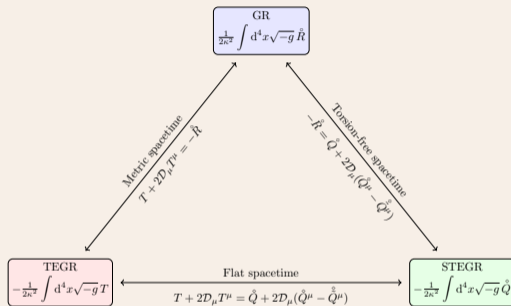
The geometric trinity



$$R = -T + B_T = -Q + B_Q$$

Einstein gravity can be written in terms of curvature, torsion, or nonmetricity.

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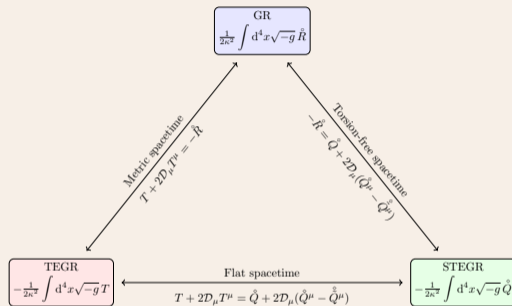
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What makes teleparallelism special

- at the Einstein level, it is equivalent to the Riemannian description through boundary-term identities;
- the connection is restricted from the start: curvature vanishes identically, so this is not a generic affine framework;
- new physics appears when the extra torsional/nonmetricity pieces are promoted beyond a pure boundary term, e.g. $f(T)$, $f(Q)$, $f(T, B)$, or scalar couplings;
- matter is typically sourced by energy-momentum, rather than generic hypermomentum.

Teleparallel corner (general curvature is zero)

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Teleparallelism is not just a change of notation: it is a restricted geometric framework with its own consistent extensions.

Poincaré gravity

A gauge approach means that gravity is built from fields associated with local spacetime symmetries.

For the local Poincaré symmetry, the basic variables are

$$e^a{}_{\mu}, \quad \omega^{ab}{}_{\mu},$$

namely a coframe/tetrad and an independent Lorentz connection.

Their field strengths are torsion and curvature:

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Metric-affine gravity

One can go beyond the Riemann–Cartan case by allowing the metric and the affine connection to be independent.

Then nonmetricity can also be present:

$$Q_{\rho\mu\nu} = -\nabla_{\rho}g_{\mu\nu} \neq 0.$$

So metric-affine gravity is the more general framework in which curvature, torsion, and nonmetricity can all participate in the dynamics:

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Gauge language can also be used in teleparallel gravity; the real distinction here is that curvature is now allowed.

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So enlarging geometry is not just a mathematical generalisation: it changes both the physical content and the consistency conditions of the theory.

- Convenient to decompose torsion as

Decomposition of torsion in the pseudo orthogonal group

$$T^\lambda{}_{\mu\nu} = \frac{1}{3} (\delta^\lambda{}_\nu T_\mu - \delta^\lambda{}_\mu T_\nu) + \frac{1}{6} \varepsilon^\lambda{}_{\rho\mu\nu} S^\rho + t^\lambda{}_{\mu\nu}.$$

using

- Vector part $T_\mu = T^\lambda{}_{\mu\lambda}$,
- Axial vector part $S_\mu = \varepsilon_{\mu\nu\rho\sigma} T^{\nu\sigma\rho}$,
- Tensor part $t^\lambda{}_{\mu\nu} = T^\lambda{}_{\mu\nu} - \frac{1}{3} (\delta^\lambda{}_\nu T_\mu - \delta^\lambda{}_\mu T_\nu) - \frac{1}{6} \varepsilon^\lambda{}_{\rho\mu\nu} S^\rho$.

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- The most general class of quadratic Poincaré gauge models that are reduced to General Relativity in the absence of torsion is:

$$S_g = \frac{1}{16\pi} \int \left[-R + c_2 \tilde{R}_{\lambda\rho\mu\nu} \tilde{R}^{\lambda\mu\rho\nu} - \frac{1}{2} (2c_1 + c_2) \tilde{R}_{\lambda\rho\mu\nu} \tilde{R}^{\mu\nu\lambda\rho} + c_1 \tilde{R}_{\lambda\rho\mu\nu} \tilde{R}^{\lambda\rho\mu\nu} \right. \\ \left. + d_1 \tilde{R}_{\mu\nu} (\tilde{R}^{\mu\nu} - \tilde{R}^{\nu\mu}) + \frac{1}{2} (m_T^2 T_\mu T^\mu + m_S^2 S_\mu S^\mu + m_t^2 t_{\lambda\mu\nu} t^{\lambda\mu\nu}) \right] \sqrt{-g} d^4 x.$$

- It is not possible to have a stable propagating torsion tensor with propagating vectors in quadratic Poincaré gauge theory for general backgrounds. Kinetic part of vectors T_μ and S_μ propagate a ghost.

Cubic Poincare Gauge Gravity

Instead of stopping at the quadratic obstruction, I extended the theory by parity-preserving cubic curvature–torsion terms,

$$\mathcal{L}_{\text{curv-tors}}^{(3)} = \mathcal{L}_{\tilde{R}TT}^{(3)} + \mathcal{L}_{\tilde{R}SS}^{(3)} + \mathcal{L}_{\tilde{R}tt}^{(3)} + \mathcal{L}_{\tilde{R}TS}^{(3)} + \mathcal{L}_{\tilde{R}Tt}^{(3)} + \mathcal{L}_{\tilde{R}St}^{(3)}.$$

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No ghost for vector sector

In this cubic branch, the ghost problem in the vector torsion sector can be removed. This gives a genuinely healthy propagating Poincaré sector to study further.

S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **109** (2024) 104075

Exact static solution

In cubic metric-affine gravity with torsion and nonmetricity, one finds an exact static, spherically symmetric black-hole solution (S. Bahamonde and J. Gigante Valcarcel, Phys. Rev. D **111** (2025) 084058),

$$ds^2 = -\Psi(r) dt^2 + \frac{dr^2}{\Psi(r)} + r^2 d\Omega^2, \quad \Psi(r) = 1 - \frac{2m}{r} + \frac{Q_{\text{geom}}}{r^2}.$$

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Why it is interesting

The metric looks like Reissner–Nordström, but the extra $1/r^2$ term is not an electric charge. It comes from intrinsic geometric charges carried by torsion and nonmetricity,

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Physical message

A familiar black-hole metric can therefore hide genuinely new geometric hair. For suitable signs of the constants H_i , one also finds a branch without an inner Cauchy horizon.

What are the intrinsic charges?

Matter can carry more than energy–momentum

In metric-affine gravity, matter may carry microstructure. In the black-hole solution, this appears through three intrinsic geometric charges:

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Why this matters

These charges survive in the vacuum exterior as integration constants of the geometry. GR has no direct analogue, because standard GR couples matter only through energy–momentum.

Atomic physics analogy

In atomic systems, orbital motion couples to intrinsic spin and produces a spin-orbit interaction,

$$\mathcal{L}_{\text{SO}} \sim \lambda(r) \mathbf{L} \cdot \mathbf{S}.$$

This is one of the standard mechanisms behind energy-level splitting.

From atomic spin-orbit coupling to gravity

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Gravitational question

Can black-hole rotation a couple to an intrinsic spin charge κ_s carried by torsion?

In other words: can gravity generate an analogue of spin-orbit interaction with a *purely geometric origin*?

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Why this is difficult

In Poincaré gravity, axial symmetry activates the full torsion sector, so finding an exact slowly rotating solution is already a highly non-trivial problem.

Exact slowly rotating solution

We found an **exact slowly rotating Kerr-like black-hole solution** with non-trivial dynamical torsion:

$$ds^2 = \Psi(r)dt^2 - \frac{dr^2}{\Psi(r)} - r^2 d\vartheta^2 - r^2 \sin^2 \vartheta d\phi^2 + 2a(1 - \Psi(r)) \sin^2 \vartheta dt d\phi, \quad \Psi(r) = 1 - \frac{2m}{r}.$$

S. Bahamonde and J. Gigante Valcarcel, Phys. Lett. B **873** (2026) 140126.

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New torsion-induced interaction

Schematically, the solution contains

$$\mathcal{L}_{\text{eff}} = \underbrace{\frac{d_1 N_1^2 \kappa_s^2}{8\pi r^4}}_{\text{static spin charge}} + \underbrace{\frac{d_1 N_1 a \kappa_s}{2\pi} F(r, \vartheta)}_{\text{new } a\kappa_s \text{ term}}.$$

Here the same function $F(r, \vartheta)$ that appears in the axial torsion controls the new interaction.

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The key new effect is a purely torsion-induced coupling between black-hole rotation a and intrinsic spin charge κ_s : a gravitational spin-orbit interaction.

S. Bahamonde and J. Gigante Valcarcel, Phys. Lett. B **873** (2026) 140126.

Axial torsion in the Dirac equation

For minimally coupled Dirac fermions, only the axial torsion mode enters:

$$\gamma^\mu \nabla_\mu \psi - \frac{i}{4} \gamma^5 \gamma^\mu S_\mu \psi + i\mu\psi = 0.$$

So the spinor is sensitive only to the axial mode S_μ , not to the full torsion tensor.

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Separability in the dirac equation

Requiring separability fixes

$$F(r, \vartheta) = \frac{3 - 4\Psi(r)}{6r\Psi(r)} \cos \vartheta + \frac{f(r)}{r}.$$

Hence the near-horizon physics is controlled by two quantities:

$$\kappa_S, \quad f(r_h).$$

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This is why the later frequency splitting can be written entirely in terms of κ_S and $f(r_h)$.

S. Bahamonde and J. Gigante Valcarcel, arXiv:2603.19140.

Near-horizon frequencies

$$\Omega_{\pm} = \omega - \frac{ak}{2mr_h} \pm \frac{3}{r_h} \left(N_1 \kappa_s - \frac{a}{m} f(r_h) \right).$$

ω : mode frequency, k : azimuthal number, a : black-hole rotation, m : mass, r_h : horizon radius.
 κ_s : intrinsic spin charge, $f(r_h)$: horizon value of the torsion function.

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Energy flux

$$\frac{dE}{dt} = \frac{1}{32mr_h} \left[(4\omega + \Omega_- - \Omega_+) |A_3|^2 + (4\omega + \Omega_+ - \Omega_-) |A_2|^2 \right].$$

Here A_2 and A_3 are the amplitudes of the two ingoing helicity components. The number flux remains positive,

$$\frac{dN}{dt} \approx \frac{1}{4} \left(|A_3|^2 + |A_2|^2 \right) > 0.$$

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Axial torsion opens a new channel for black-hole energy extraction, even without standard fermionic

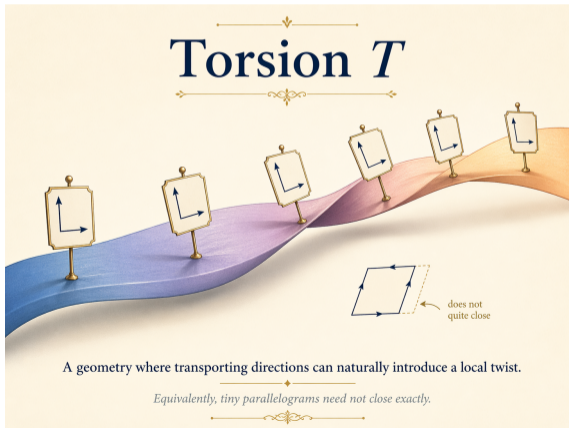
- Enlarging spacetime geometry leads to genuinely new gravitational effects beyond General Relativity.
- Torsion and nonmetricity can support new black-hole structures, new interactions, and new consistency conditions.
- The examples shown today illustrate that these theories are not only geometrically richer, but can also lead to concrete physical consequences.

Main message: changing the geometry changes the physics.

Thank you for listening!

Questions?

Torsion T



Nonmetricity

